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Process Optimisation of Beer Fermentation through Dynamic Simulation

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1. Beer Fermentation: Background

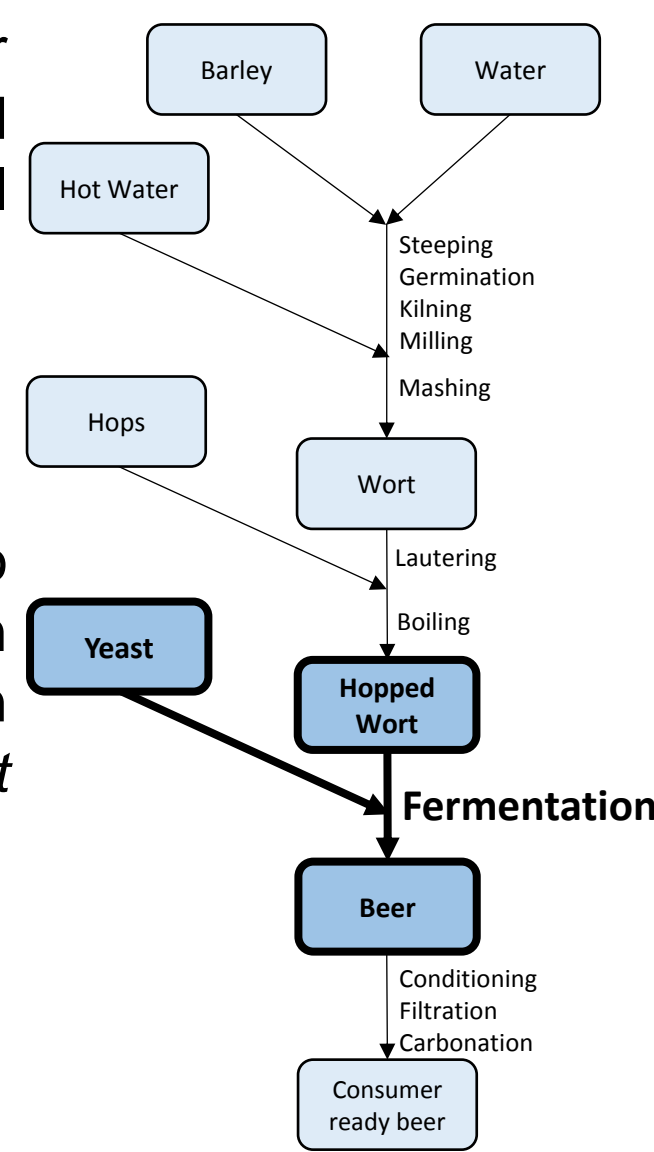
Fermentation is an essential step in beer brewing: yeast is added to sugars released from barley grain, which ferment into ethanol (EtOH) and higher alcohols. The process is:

- Time-consuming (>120 hours)
- Energy-intensive (cooling)
- Highly complex (200+ species)

Because this chemical system is sensitive to the imposed temperature profile, fermentation success and efficiency strongly depend on the selection and implementation of the most effective dynamic temperature manipulation.

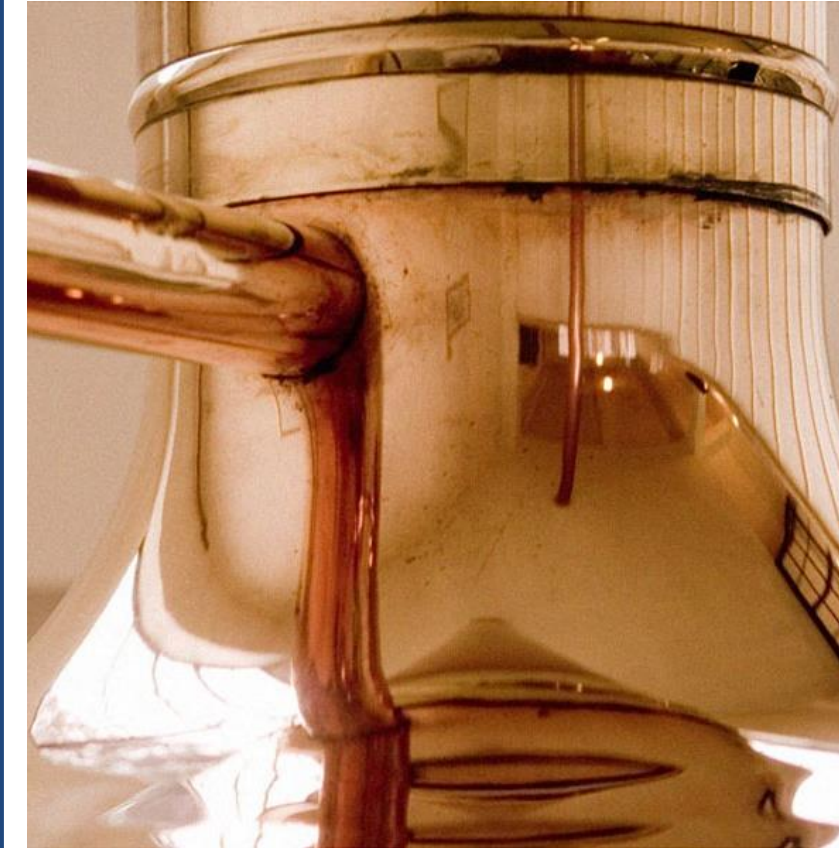


Fermentation tanks
(WEST Brewery,
Glasgow, UK)



2. Process Optimisation: Project Objectives

This research project has evaluated published kinetic models and then focused on optimal operating conditions, to improve plant performance:

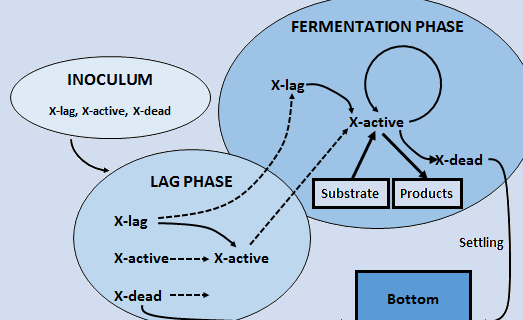


Mashing tanks
(WEST Brewery, Glasgow, UK)

- Literature review and evaluation of prior published kinetic models and fermentation optimisation studies.
- Computational implementation of the most reliable kinetic model for fermentation, and assessment of a range of published operating temperature profiles (MATLAB®).
- Computational identification of the optimal temperature manipulation profile via stochastic optimisation.
- Experimental validation vs. WEST industrial production plant data.

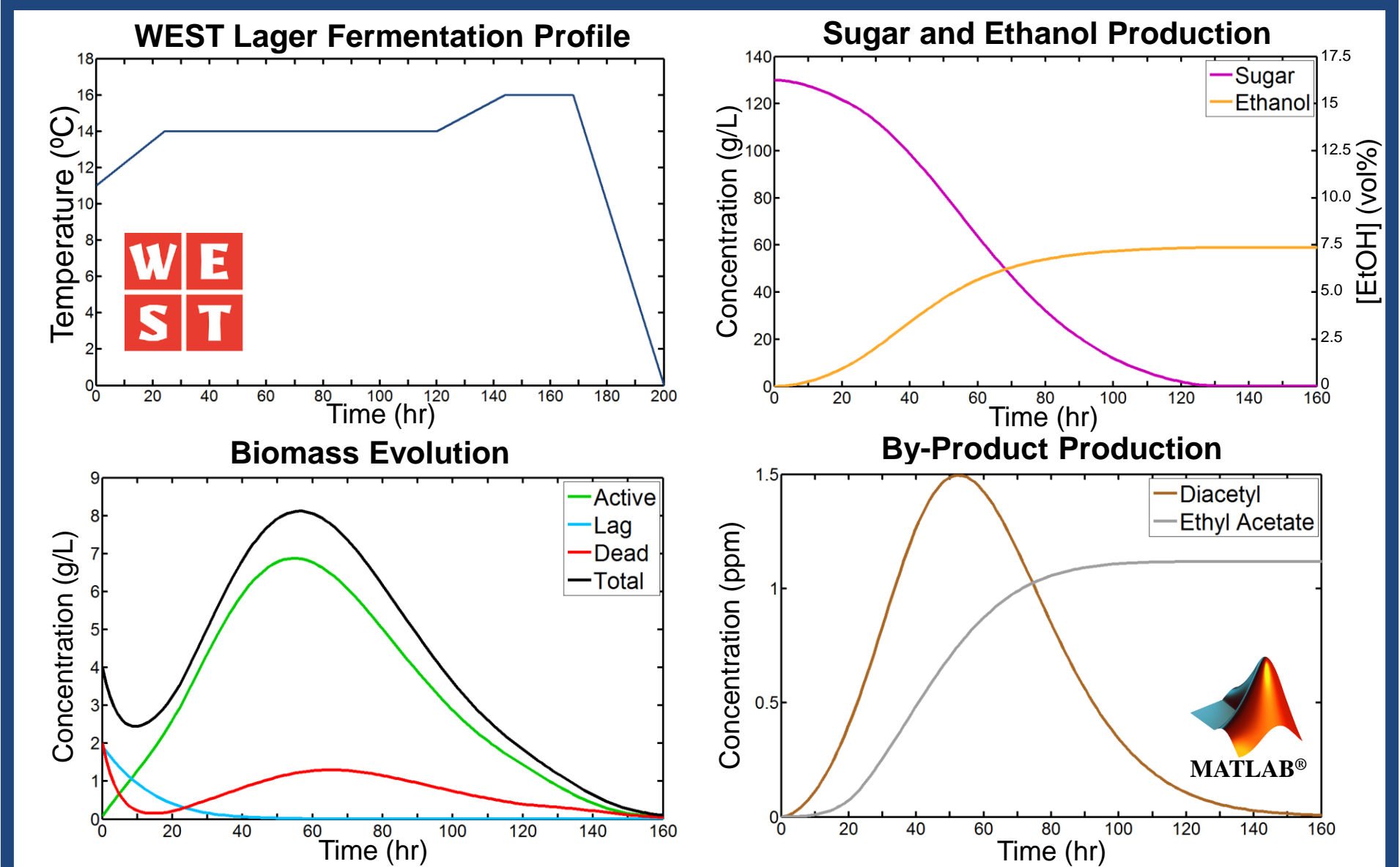
3. Dynamic Mathematical Model of Fermentation

Beer Fermentation Kinetic Model (B. de Andrés-Toro, 1998)	
Alcohol	$\frac{dC_E}{dt} = f \cdot \mu_E \cdot X_{act}(t); \quad f = 1 - \frac{C_E(t)}{0.5 \cdot C_{S0}}, \quad \mu_E = \frac{\mu_{E0}(T) \cdot C_S(t)}{K_E(T) + C_S(t)}$
Sugar	$\frac{dC_S}{dt} = -\mu_S \cdot X_{act}(t); \quad \mu_S = \frac{\mu_{S0}(T) \cdot C_S(t)}{K_S + C_S(t)}$
Yeast	$\frac{dX_{lag}}{dt} = -\mu_{lag} \cdot X_{lag}(t)$ $\frac{dX_{dead}}{dt} = -\mu_{SD} \cdot X_{dead}(t) + \mu_{DT} \cdot X_{act}(t)$ $\frac{dX_{act}}{dt} = \mu_x \cdot X_{act}(t) - \mu_{DT} \cdot X_{act}(t) + \mu_L \cdot X_{lag}(t)$
By-Products	$\frac{dC_{EA}}{dt} = R_{EA}(T) \cdot \frac{dC_S}{dt}$ $\frac{dC_{DY}}{dt} = \mu_{DY} \cdot C_S(t) \cdot X_{act}(t) - \mu_{AB} \cdot C_{DY}(t) \cdot C_E(t)$



NOMENCLATURE
 μ_x Substrate consumption rate
 R_i Stoichiometric coefficient
 C_i Concentration
 i Species
 f Inhibition factor
 EA Ethyl acetate
 DY Diacetyl compounds
 lag Latent yeast cells
 act Active yeast cells
 $dead$ Dead yeast cells

4. Dynamic Simulation of Industrial Operation



5. Stochastic Optimisation of Fermentor Operation

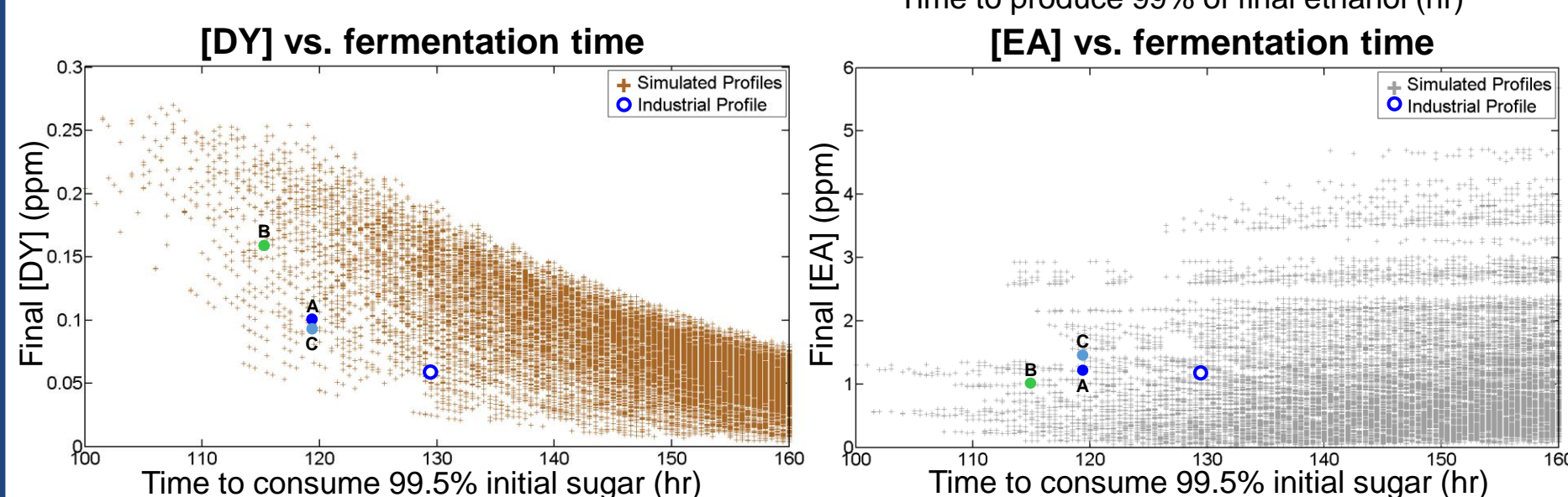
- **Ensemble:** 175,000 unique profiles (MATLAB® run time: 1 hr only!)
- Rapid, comprehensive evaluation of all output profiles for performance

T Profile Generation Constraints:

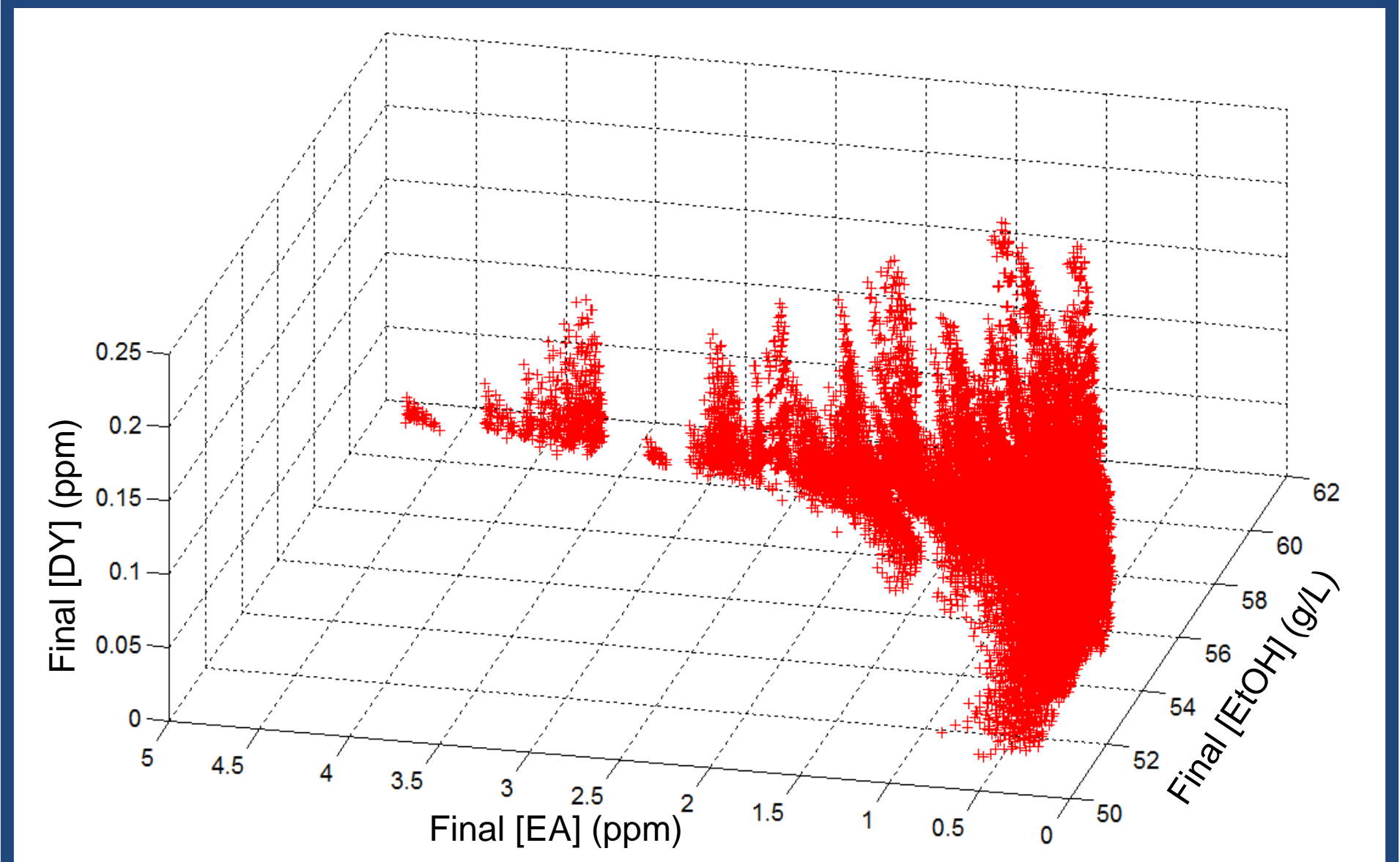
$$9^\circ\text{C} \leq T \leq 16^\circ\text{C}$$

$$T_t \geq T_{t-1}; t < 80 \text{ hr}$$

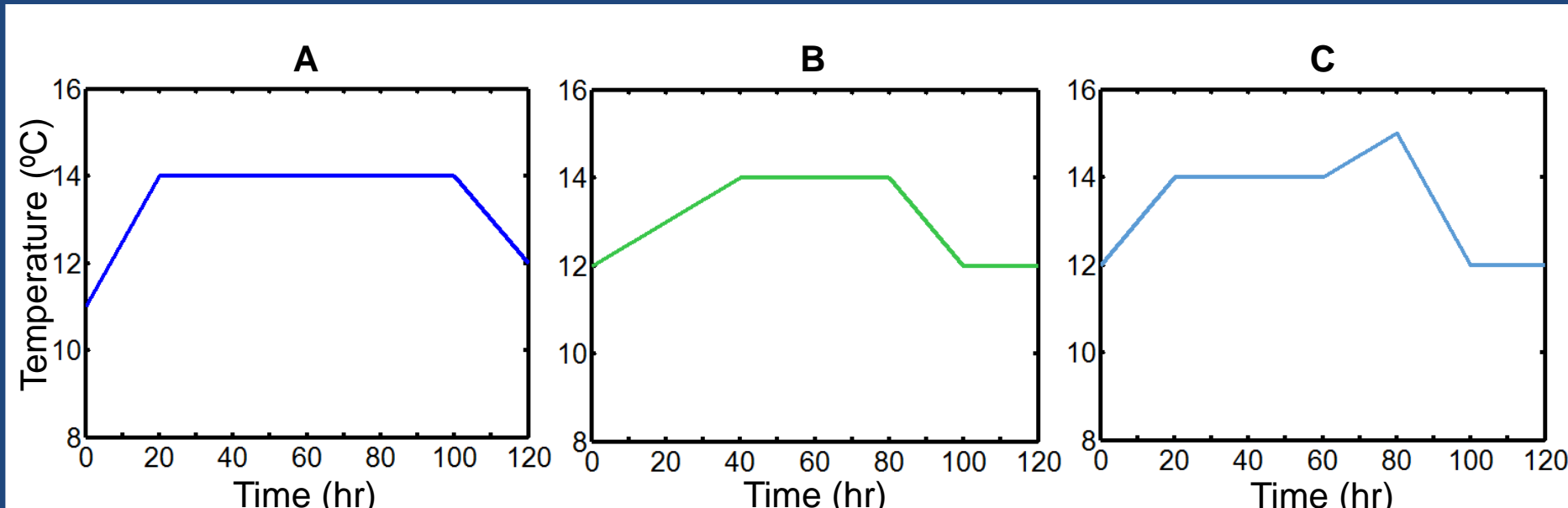
$$T_t \leq T_{t-1}; t \geq 80 \text{ hr}$$



6. Attainable Envelope of Product Compositions



7. Fermentation Process: Operational Improvements



Parameter	Units	Existing WEST Industrial Manipulation	New Operational Improvements		
			A	B	C
Fermentation time	hr	129.5	119.5	115.0	119.5
EtOH concentration	g/L	59.0	58.9	58.0	58.9
EA concentration	ppm	1.16	1.19	0.99	1.28
DY concentration	ppm	0.06	0.10	0.16	0.09

8. Conclusions

- The de Andrés-Toro (1998) model reliably describes beer fermentation
- Performance of published operating profiles is accurately predicted
- Simulation-based optimisation determines key beer quality attributes
- Three new profiles (A, B, C) demonstrate clear process improvements
- Optimal operating temperature profile accelerates beer fermentation
- Fermentation time is minimised without any loss of product quality
- Experimental validation of the model vs. WEST plant data under way

9. Literature References

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